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A Configurable Solid State Power Management And Distribution System

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ABSTRACT

Future vehicle power systems must achieve greater flexibility and reliability than those used in previous generations. New functions that enhance safety, such as arc detection and wiring integrity verification, are essential for new systems. Embedded autonomous control, and fault correction can be built into Fault Tolerant Processors that integrate into a vehicle Open System Architecture. This approach will provide status and fault detection information to maintenance interfaces and provide fault correction. Safety is enhanced by the prevention of dangerous restarts from crew and personnel. The embedded features allow for pre-flight mission configuration to setup systems before takeoff and on-board and off-board maintenance control. This enables operators to evaluate power system health and history to help reduce turn around time. A solid-state switch that integrates these essential capabilities demanded by the industry for future power systems and fault correction and health status power system is presented.

INTRODUCTION

The development of a Configurable Solid State Power Management And Distribution system (PMAD) will lower overall costs, maintenance times, and increase the safety of the vehicle. The PMAD system is capable of being controlled and configured remotely as well as capable of reporting back detailed power system status to the master control system or ground support equipment. This operation capability can be integrated into either a new vehicle system or retrofit in a previous generation heritage system during a system upgrade.

With new air and spacecraft evolving from existing proven designs, as well as clean slate designs, demands on the vehicle power systems are increasing greatly. As more and more functions are being turned over to computers and electromechanical devices, the power requirement for computational equipment increases. Eliminating hydraulic systems introduces the need to supply, control, and protect high power electromechanical actuators. Also, as entertainment and business systems access is being integrated into aircraft seats, more power cables are being placed close to passengers, which will require new safety approaches. Human error in resetting tripped circuit breakers has lead to problems during flight.

Events of this nature may be eliminated with a self-monitoring power system. Safety of crew, passengers, and vehicle can be increased by a power management system that can monitor and self evaluate the status of the power system itself. A fault tolerant power system that would not require human intervention for decisions would eliminate human errors such as the one mentioned above from happening. By the power system becoming a system of systems through Integrated Vehicle Health Management (IVHM) and Avionics, the power system becomes not only safer but also more efficient from a vehicle point of view. The IVHM system can be used to evaluate the power system conditions under a degraded mode. The IVHM system can give suggestions for a crew to accept to allow the system to be configured to operate in a more efficient manner and conserve power by shutting down systems that are not needed when a piece of equipment has failed.

By being remotely controlled and not requiring direct human intervention, the PMAD eliminates the need for a circuit breaker panel and allows control to be autonomous and/or allows control through crew interface panels and ground support equipment. This also allows the PMAD units and devices to be located close to the loads that are being controlled and protected, thus reducing the need of long, heavy gauge wiring. This will shorten cable lengths, reduce weight, increase power efficiency, decrease power loss due the parasitic impedance in long cables, eliminate mechanical circuit breakers and eliminate the arc points that come with mechanical contacts.

The arc detection, fault correction and ground fault circuit interrupt (GFCI) functions via the Solid State

Power Controller (SSPC) utilize an embedded micro-controller or Digital Signal Processor (DSP) for processing. Each SSPC contains the means to test wiring in the vehicle automatically upon suspicion of an arc event. The SSPC can test a wire per instruction of maintenance crews using the Damage Wire Detector/Locator (DWDL) integrated inside the SSPC. By using the PMAD status to virtually predict suspected problems within the vehicle and have the vehicle's avionics system provide information in advance to maintenance depots via dedicated network ports, ground crews can have equipment and replacement parts available upon arrival of the vehicle. This will allow the vehicle to be repaired and returned to service faster than having to await the arrival and then troubleshoot the vehicle. The SSPC also allows for an autonomous restart of a tripped SSPC upon power bus recovery, and at the same time prevents dangerous resetting of SSPCs under certain pre-configured conditions.

PMAD DESIGN AND APPLICATION

The main thrust of a modern PMAD system design is to increase vehicle safety and reliability. The proposed method in this paper is to approach reliability for the PMAD system through a fault tolerant redundant design. On the vehicle side, the PMAD increases vehicle safety and reliability by monitoring the systems it has interfaces with for possible failure indications. This includes items unique to power systems, such as arc detection and wiring degradation, or interfacing to the IVHM system to determine the probable source and cause of failure and appropriate action.

A solid state programmable PMAD system provides considerable flexibility in system level architecture. To minimize wiring weight, two architectures are primarily considered. Both designs utilize an operator command remote interface with the semi-autonomous or a fully autonomous PMAD system operating in a centrally located position. This can consist of a single unit with command/control functions and power switching circuitry all in one box or a unit with some or all of the power switching circuitry remotely located near the user power device. Either architecture will significantly minimize the wiring weight by reducing the distance between the Power Distribution Units (PDU) and the power device. In such architecture, the only significant wire run would be the main and possibly the auxiliary power line instead of the multiple lines to the individual devices. Each case could have the basic functions programmable so the switching would remain the same for either architecture. It is estimated that the distributed wire lengths can be reduced to approximately 25 feet or less per output channel when the PDUs are placed among the loads. This also reduces the amount of bulkhead passthroughs and connectors. An example PMAD distribution architecture is shown in Figure 1. The redundant avionics busses also represent the IVHM interfaces.

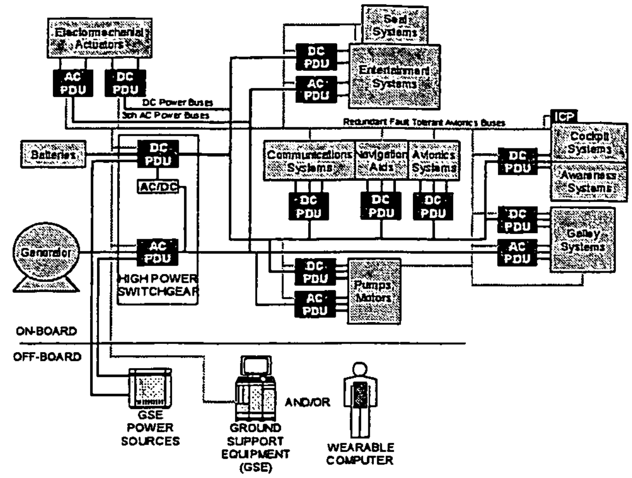


Figure 1. Generic Power Distribution and Management System Block Diagram

Autonomous on-board operations that the IVHM system manages are the gathering of fault data and setting the power system to operate more efficiently in the event of degraded mode of operations. The fault data may be transmitted to the ground for advanced evaluation, and ground crews can have the appropriate equipment and replacement parts waiting for arrival. The Off-board operations allow the ground maintenance crew to download fault data for evaluation and also allow them to operate systems for a centralized location. The Ground Support Equipment (GSE) is capable of controlling each SSPC on-board the vehicle.

PMAD SYSTEM DEVICES BEING PRESENTLY USED OR DEVELOPED

An example of a modern Solid State Power Distribution Unit that is integrated into a PMAD system is the Solid State Power Control Module (SSPCM), shown in Figure 2. The SSPCM is presently aboard the International Space Station and operates in a semi-autonomous mode controlling various payloads and computing equipment. Once setup through either another computer system or setup by an astronaut via a simple RS-232 port on a Laptop computer, the SSPCM operates without user intervention. Using the internal solid-state programmable circuit breaker, a power user is constantly monitored and real time current data relayed to the end user. If a power user exceeds a set power profile and current setting the breaker will trip. The SSPCM may be configured to simply flag the remote user or recycle power at a set interval, giving the unit an automated recovery sequence. The SSPCM also provides for automatic controlling of resources. For instance, when the power used exceeds the power available the payloads are automatically released based on a load criticality table. The concepts described in this paper build upon proven concepts, while providing an even greater level of safety and control. This is accomplished by implementing various tests either automatically or commanded for both wiring and system

faults that might not trip a circuit breaker, or even a solid-state unit.

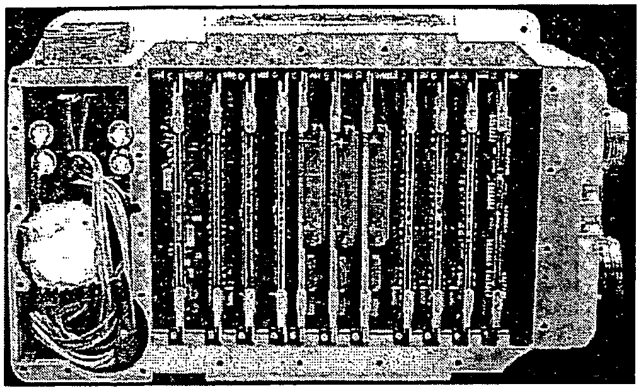


Figure 2. International Space Station version of the SSPCM.

Designs performing the same functionality, but using COTS components can be designed and built at a fraction of the size. The unit size in Figure 2 is driven to a large extent by the thermal dissipation. It has integrated 120V to 28V DC-DC conversion and is capable of 2200W of 28V output power. An example of a PMAD with fully digital and programmable SSPCs and COTS components is shown in Figure 3. This design can be readily modified for a range of input voltages and is capable of controlling up to 16 output channels.

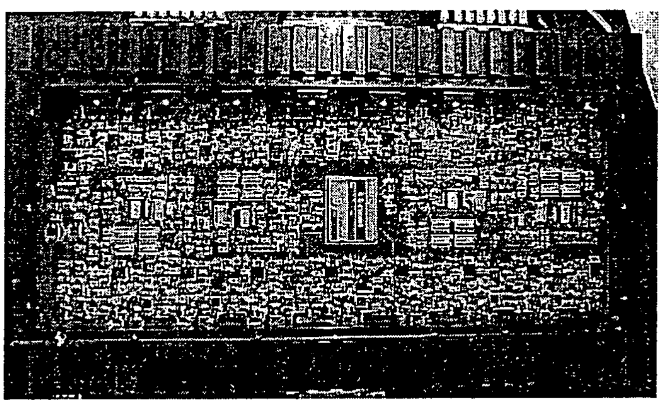


Figure 3. Digitally Programmable Solid State Power Controller

VEHICLE SAFETY AND ARC FAULT DETECTION AND WIRING DEGRADATION

As wiring harnesses and vehicles age, the probability of significant failures due to wiring harness failures and insulation goes up significantly. These can range from simple charring of wiring to arcing and fires, resulting in loss of vehicle and life. Several high profile commercial jet losses have been attributed to wiring and or insulation failures that resulted in arcing events that caused fires. A loss of an AC Phase A power three years ago on the Space Shuttle (STS-93), four seconds into the flight was also attributed to a short in the wiring harness. Unfortunately no method exists for detection and squelching of these types of failure modes. At least one commercial airline is initiating a program to replace vehicle wiring at planned intervals to eliminate the aging wire problem. However, even an expensive plan like this cannot accommodate all premature failures due to things such as:

- Debris
- Chaffing
- Moisture infiltration
- Premature aging of insulation
- Erroneous installation either during assembly or subsequent repair
- Damage by technician during other vehicle system work/repair

While life cycle cost and ease of vehicle control is a significant design driver in a new PMAD system, the main design drivers are overall increased vehicle reliability and safety of the human crew and passengers. Thus two unique features are being integrated into the PMAD architecture to detect failures before significant damage has occurred. First is the detection of arcing and quick suppression of the arc. The second is wiring degradation detection prior to arcing or other failure mode.

Arc Detection and Wiring Degradation Module

A Programmable Solid State Circuit Breaker/Switch (PSSCB/S) With Arc Detection and Damaged Wire Detector/Locator Module was designed as an upgrade for the unit shown in figure 3. A prototype of this module is shown in Figure 4.

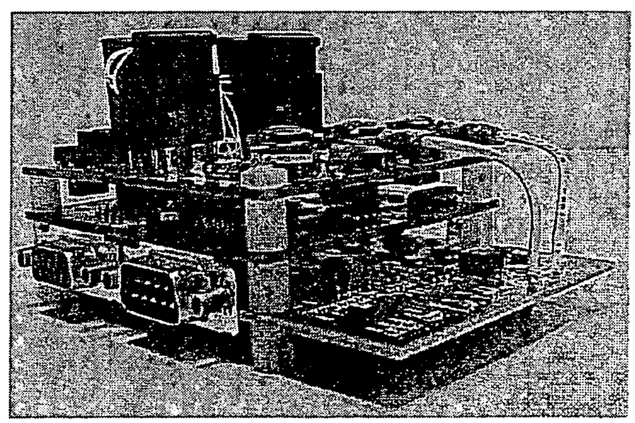


Figure 4. Prototype PSSCB/S with Arc Fault Detection and Damaged Wire Detector/Locator Module.

The SSPC provides an excellent base platform on which to build arc detection and integrated wire testing due to the inherent load monitoring functions. The PSSCB/S module integrates several features critical to arresting wiring failures prior to actual damage, such as:

- Integrated over current, over/under voltage and over/under temperature monitoring.
- User selectable current, voltage and temperature limits from Maintenance Testing Equipment.
- Short circuit protection and no turn-on into a shorted

circuit.

- Integrated Arc Fault, GFCI and Damaged Wire detection.
- Fault detection and health status via serial data bus interface.

Combining the above features into a modular network ready package benefits the entire system. The modularity of the PSSCB/S module not only saves space with its design, but it will also save weight in wiring by being co-located with the load. An estimate of the weight of wire capable of 30kW at 270Vdc is approximately a half of a pound per foot. The cable weight and losses are reduced by minimizing the lengths of wiring, which is accomplished through the capability of locating the PDU devices near the load.

The design can be integrated into a standard circuit breaker size, as shown in figure 5. Another approach is to replace an entire circuit breaker panel with a semi-autonomously controlled solid state PDU type panel, as the one shown in Figure 9. This packaging allows the power controllers to fit into same the area where the circuit breaker panel was located. On other approach is to incorporate remotely controlled PDU similar to the unit shown in figure 3. This would allow the power controllers to be located closer to the loads that are being protected. The scalability of the design can accommodate both legacy aerospace vehicles and today's clean sheet vehicle designs.

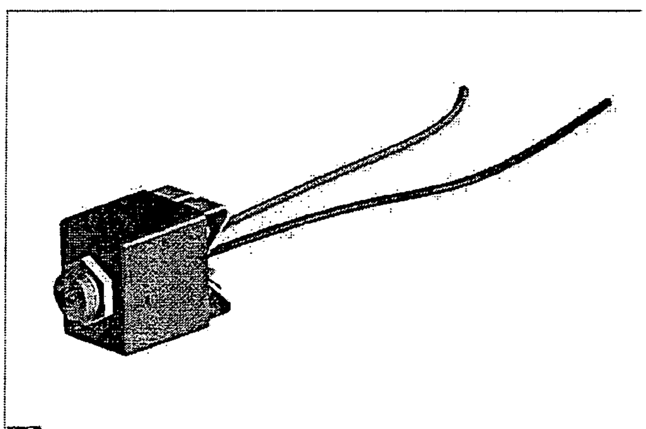
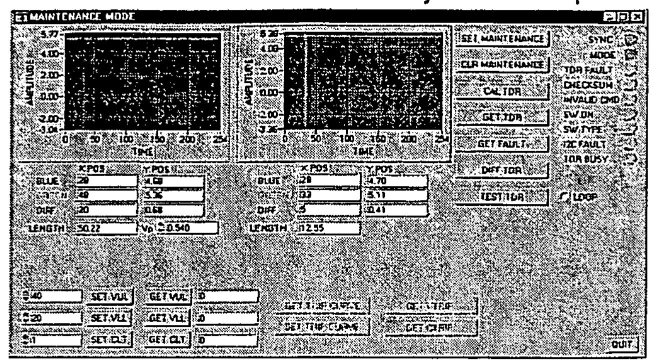


Figure 5. Example of a Programmable Solid State Circuit Breaker.

The PSSCB/S also offers an array of built-in safety features. The integrated health and status functions of the device not only serve as safety features but also as maintenance features. The device not only stores the type of fault, but it also stores the location of the fault along the wire. This will drastically reduce maintenance times by giving a location to examine when the arc event may have only browned an area instead of having a complete burn through. Features such as Ground Fault Circuit Interruption (GFCI) protection to flag any grounding faults are also built into the device. The microcontroller automatically shuts off the device if a cable or connector is changed or if an arc event was previously detected. In the case of microcontroller failure, the device includes watchdog circuitry for placing the output in safe mode to preserve any critical data or maintenance records. Any firmware updates



needed for the microcontroller may be updated via serial maintenance port.

Figure 6. Damaged Wire Detector/Locator Maintenance and Analysis Display.

An example display from a wiring harness test is shown in Figure 6. The left view shows data stored from initial training session on a fifty-foot wire with a load. The right view shows data from a short that is located approximately 12 1/2 feet down the same fifty-foot wire with load. This is a good example of the type of maintenance screen which allows the technician to save time when looking for a damaged wire. These maintenance screens are based on off the shelf wire testing displays to minimize training of personnel to use the system. Additional damaged wire locator analysis software tools are being developed at this time that will autonomously compare data to minimize error in human eye comparison of the data on the display screens.

PMAD FAULT TOLERANCE AND REDUNDANCY

In order to reduce PMAD and system cost, as well as use the latest generation of electronic components, the use of Commercial Off The Shelf (COTS) parts is utilized. For the purpose of this paper COTS is defined as any commercial available component whether it is commercial, industrial, or military grade. In order to increase PMAD system reliability, while simultaneously decreasing the cost (both purchase and maintenance or life cycle costs) the use of redundant components is needed.

In order to assure high reliability and a low cost for future vehicle programs, enabling technology items need to be addressed. Some of the major items include Fault Management (both BIT and hosting IVHM), Power, Environmental Considerations, System Reliability, Modularity, and overall System Cost with emphasis on recurring/operational costs. The heart of the fault containment and resultant reliability is the Fault Tolerant Processor Module (FTPM). Scalable system level fault tolerance can be achieved by first providing redundant resources at the Line Replaceable Unit (LRU) and lower levels, e.g. redundant modules within a LRU or redundant resources on the same module. Then, a N-to-N LRU level Cross-Channel-Data-Link (CCDL) design (i.e. each LRU is directly connected to every other LRU in the redundant configuration) enables the system configuration to be scalable from N to 1. The necessary features of the CCDL include, as a minimum, synchronization, voting and/or comparison design, and fault management of the CCDL hardware and operation. An example of PDU devices in a PMAD system interconnected with fault tolerant channels is shown in Figure 7.

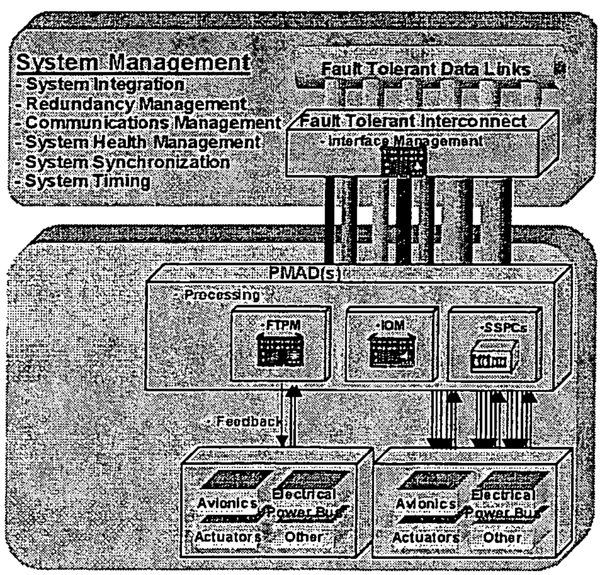


Figure 7. PMADs interconnect via FTPM and Fault Tolerant Data Links.

To achieve transparency, hardware fault tolerant features (such as self-checking pairs and Error Detection and Correction codes) and software fault management routines are required. Fault management routines can be largely classified into two categories: 1) building block or infrastructure fault management, and 2) system or application fault management.

The PMAD system fault tolerant scheme offers the following benefits to the system:

- Multi-layered protection against single event upsets or other errors and thus improves safety and enables flight/ launch with failure
- Tolerant of N faults with N+1 channels, instead of N+2, reduces hardware cost and weight and increases reliability
- Eliminates false alarm with added confirmation step
- Subsystem level fault containment maximizes the ability to achieve single LRU fault ambiguity performance
- Single LRU level fault ambiguity performance reduces cannot-duplicate, reduces maintenance costs, and improves turnaround
- Improves confidence with verified fault coverage performance
- Co-location of flight-critical and non-critical functions

One of the major advantages on a transparent scalable system is the ease with which additional units can be added to increased system reliability as required. Figure 8 shows some examples of redundant configurations to ensure system reliability from unmanned to the most flight critical manned systems, such as Space Shuttle type architecture.

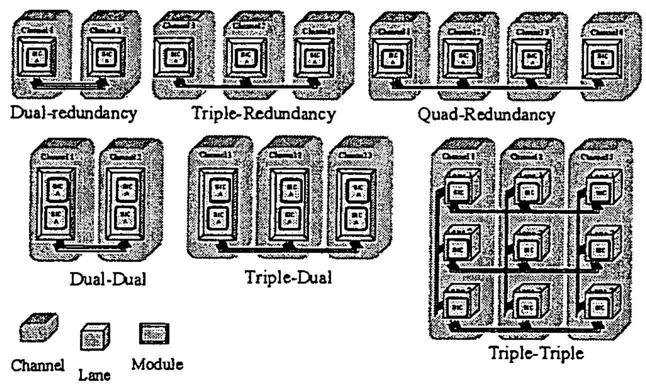


Figure 8. Example Redundancy Schemes.

VEHICLE INTEGRATION

Several options are available pending on vehicle size, if it is a new design or retrofit, and reliability requirements. The basic requirements of increased safety of flight and reduced life cycle costs will determine the optimal PDU location. Remotely distributed PDUs may be the solution for a military vehicle that may sustain combat damage. For a commercial vehicle, however, a central location may help reduce life cycle cost by allowing easier access to the system.

Systems in legacy vehicles benefit from new features such as solid state power controllers, arc fault detection and/or integrated wire testing face the difficulties of having limited allocated areas where circuit breaker panels exist. Changing out wiring harnesses to meet new PDU architectures is not cost effective and retrofit times are great. An option to package the SSPCs and integrated arc fault/wire testing capabilities is possible. By applying the solution as a power density versus area

approach, the desired functions can be implemented while still maintaining the same power cable arrangement. The power control and fault detection functions can be integrated into a panel assembly that will fit into the area where the previous circuit breaker panel was located. An example of the Power Distribution Assembly (PDA) is shown in Figure 9.

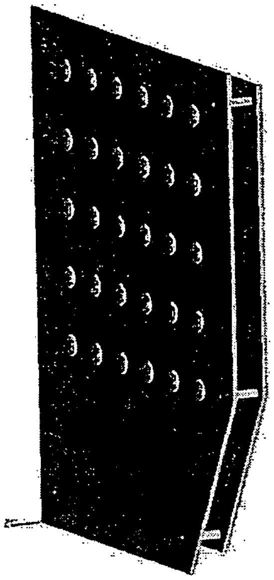


Figure 9. Power Distribution Assembly (PDA) Front View.

Even though the power control devices are solid state and can be remotely controlled, they can also be controlled and monitored via discrete inputs and outputs. This may be an option for those who do not wish to add additional wiring for the communications data bus. A mechanical button switch accomplishes ON/OFF control and a light indicator indicates trips. However, this does defeat the purpose of eliminating mechanical devices. Even though the human interface control is mechanical, the load protection and fault detectors are still solid state.

The Circuit Board Assembly (CBA) that is located on the back of the mounting panel can be laid out in an arrangement to match the cable harnesses that are already in place. This allows the cabling harnesses to be reconnected without or with minimal modification. An example of the CBA layout is shown in Figure 10.

To recover the fault data, the data communication bus that interconnects SSPCs is embedded into the CBA and can be accessed via a maintenance interface port to GSE.

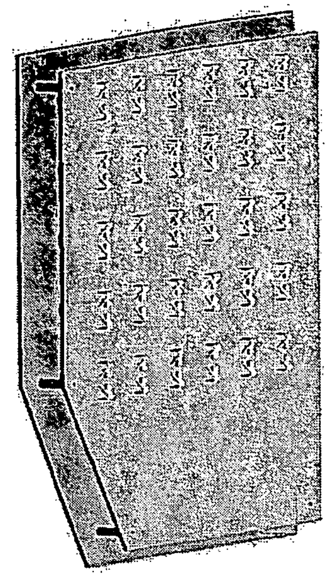


Figure 10. Power Distribution Assembly (PDA Back View.

For clean sheet designs, the Power Distribution Unit (PDU) approach may be more desirable. The approach is to use the Open System Architecture (OSA) Common Modular Avionics (CMA) housing concept with the appropriate modifications to accommodate for the thermal differences between a power unit and an avionics box. The same approach can be taken to house any power conversion units that are required. This maintains a commonalty between products and allows for easy integration of standard commodity products. Figure 11 shows an example of an OSA PDU.

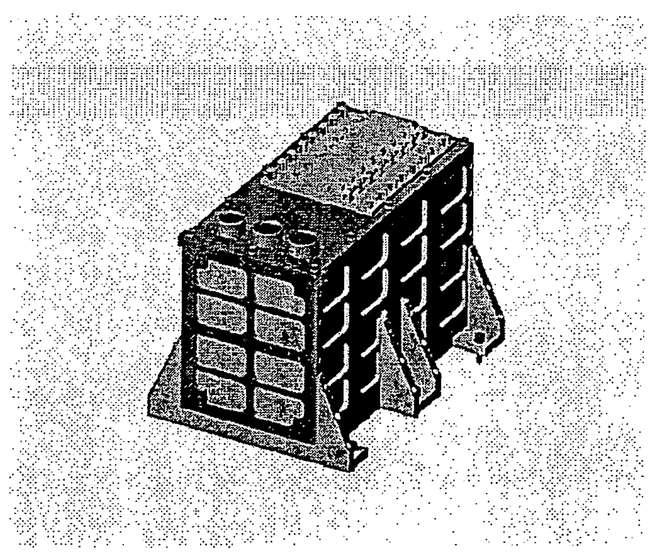


Figure 11. Open System Architecture Power Distribution Unit (PDU).

An example of how the OSA PDUs may be distributed throughout a vehicle power architecture is shown in Figure 1. It is also possible to locate the SSPC devices

within each OSA avionics unit. The communication and control of each device would remain the same as that previously described.

CONCLUSION

It is possible and feasible to design a power architecture that can operate autonomously or semi-autonomously and provide a measurable increase in safety, efficiency and cost reduction. In particular, the new arc detection and suppression and wiring degradation detection features will help minimize or eliminate a major source of vehicle damage/loss and loss of life. The use of such techniques will dramatically reduce maintenance and life cycle costs, due to reduced repairs and inspection, and will minimize or eliminate scheduled replacement of wiring harnesses due to fear of in-flight failures. The use of state of the art components, in conjunction with modern redundancy and fault management techniques, will simultaneously increase system reliability, reduce system weight, and reduce PMAD costs. At the same time, the architecture is flexible enough to meet the needs of legacy vehicles as well as clean sheet designs. The added fault detection requirements of legacy and clean sheet systems are similar, so that the same functionality of the PDU devices can be used in both cases. The packaging becomes the major driver between the two types of vehicle designs. However, due to the modularity of the basic design concept, the functionality can be scaled to meet either need. For an existing design, additional challenges exist; but through the use of the inherent flexible design features and the use of existing circuit breaker panels or other heritage operator interfaces, a highly reliable and fault tolerant PMAD system can be used in heritage as well as new vehicle designs.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AC: Alternating Current

BIT: Built In Test

CBA: Circuit Board Assembly

CCDL: Cross Channel Data Link

CMA: Common Modular Avionics

COTS: Commercial Off The Shelf

DC: Direct Current

DSP: Digital Signal Processor

DWDL: Damaged Wire Detector/Locator

FTPM: Fault Tolerant Processor Module

GFCI: Ground Fault Circuit Interrupt

GSE: Ground Support Equipment

IVHM: Integrated Vehicle Health Management

LRU: Line Replaceable Unit

OSA: Open System Architecture

PDA: Power Distribution Assembly

PDU: Power Distribution Unit

PMAD: Power Management And Distribution

PSSCB/S: Programmable Solid State Circuit/Switch

SSPC: Solid State Power Controller

SSPCM: Solid State Power Control Module